

# **Theoretical Studies of Time Dependent/Independent Radiative Transfer Including Inelastic Scattering for Both Active and Passive Sources**

George W. Kattawar  
Dept. of Physics  
Texas A&M University  
College Station, TX 77843-4242  
phone: (409) 845-1180 fax: (409) 845-2590 e-mail: [kattawar@tamu.edu](mailto:kattawar@tamu.edu)  
Award #: N000149510275  
<http://people.physics.tamu.edu/trouble/work.html>

## **LONG-TERM GOALS**

Long term goals are to obtain a thorough understanding of the behavior of the complete Stokes vector both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we want to see how one can use polarization information to obtain more information about the IOP's of both oceanic and littoral zone constituents. We also want to explore the efficacy of polarimetric time-of-flight lidar techniques in determining salinity and speed of sound in the ocean as well as submersible object detection. We want to continue our collaborative program in ocean polarimetry with the group in Minsk headed by Dr. Eleonora Zege.

## **OBJECTIVES**

It is our major objective to find new and innovative ways in which polarimetry can be used to determine not only inherent optical properties but also certain physical properties such as temperature and salinity of ocean water. We also want to further develop a new method of imaging which we would like to label "Mueller matrix imaging" (MMI). With this method we want to determine how much more information we can obtain about target features by using elements other than  $S_{11}$  (ordinary radiance) of the Mueller matrix

We wish to continue our collaborative program with the Radiative transfer group in Minsk, Belarus headed by Dr. Eleonora Zege. Our combined objectives for this program are as follows:

- a) Simplification of the equations for the elements of the Green's matrix for the VRTE. Development and testing of an algorithm and code to compute the Stokes vector in an atmosphere-ocean using the multi-component approach (MCA).
- b) Computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination employing Monte-Carlo and MCA codes. Comparison of results and elucidation of ways to improve both codes.
- c) Development of the simplified equations for propagation of a linearly polarized beam in order to study the Stokes vector in the on-axis region for both backward and forward directions.
- d) Development of the code to compute the Stokes vector in the on-axis region for a polarized narrow beam and compare with experimental data.

| Report Documentation Page  |                                    |                                     | Form Approved<br>OMB No. 0704-0188                               |                                    |                                    |
|--|------------------------------------|-------------------------------------|--|------------------------------------|------------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. |                                    |                                     |  |                                    |                                    |
| 1. REPORT DATE<br><b>30 SEP 1999</b>   | 2. REPORT TYPE                     |                                     | 3. DATES COVERED<br><b>00-00-1999 to 00-00-1999</b>              |                                    |                                    |
| 4. TITLE AND SUBTITLE<br><b>Theoretical Studies of Time Dependent/Independent Radiative Transfer Including Inelastic Scattering for Both Active and Passive Sources</b>  |                                    |                                     | 5a. CONTRACT NUMBER  |                                    |                                    |
|  |                                    |                                     | 5b. GRANT NUMBER   |                                    |                                    |
|  |                                    |                                     | 5c. PROGRAM ELEMENT NUMBER                                       |                                    |                                    |
| 6. AUTHOR(S)   |                                    |                                     | 5d. PROJECT NUMBER   |                                    |                                    |
|  |                                    |                                     | 5e. TASK NUMBER  |                                    |                                    |
|  |                                    |                                     | 5f. WORK UNIT NUMBER   |                                    |                                    |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><b>Texas A&amp;M University, Department of Physics, Galveston, TX, 77843</b>   |                                    |                                     | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER                      |                                    |                                    |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  |                                    |                                     | 10. SPONSOR/MONITOR'S ACRONYM(S)                                 |                                    |                                    |
|  |                                    |                                     | 11. SPONSOR/MONITOR'S REPORT<br>NUMBER(S)                        |                                    |                                    |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release; distribution unlimited</b>  |                                    |                                     |  |                                    |                                    |
| 13. SUPPLEMENTARY NOTES  |                                    |                                     |  |                                    |                                    |
| 14. ABSTRACT   |                                    |                                     |  |                                    |                                    |
| 15. SUBJECT TERMS  |                                    |                                     |  |                                    |                                    |
| 16. SECURITY CLASSIFICATION OF:  |                                    |                                     | 17. LIMITATION OF<br>ABSTRACT<br><b>Same as<br/>Report (SAR)</b> | 18. NUMBER<br>OF PAGES<br><b>7</b> | 19a. NAME OF<br>RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>   | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b> |  |                                    |                                    |

- e) Improving the codes for computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination. Computation via improved codes. Data comparison.

## **APPROACH**

We have developed some very sophisticated Monte Carlo codes to handle the following types of problems:

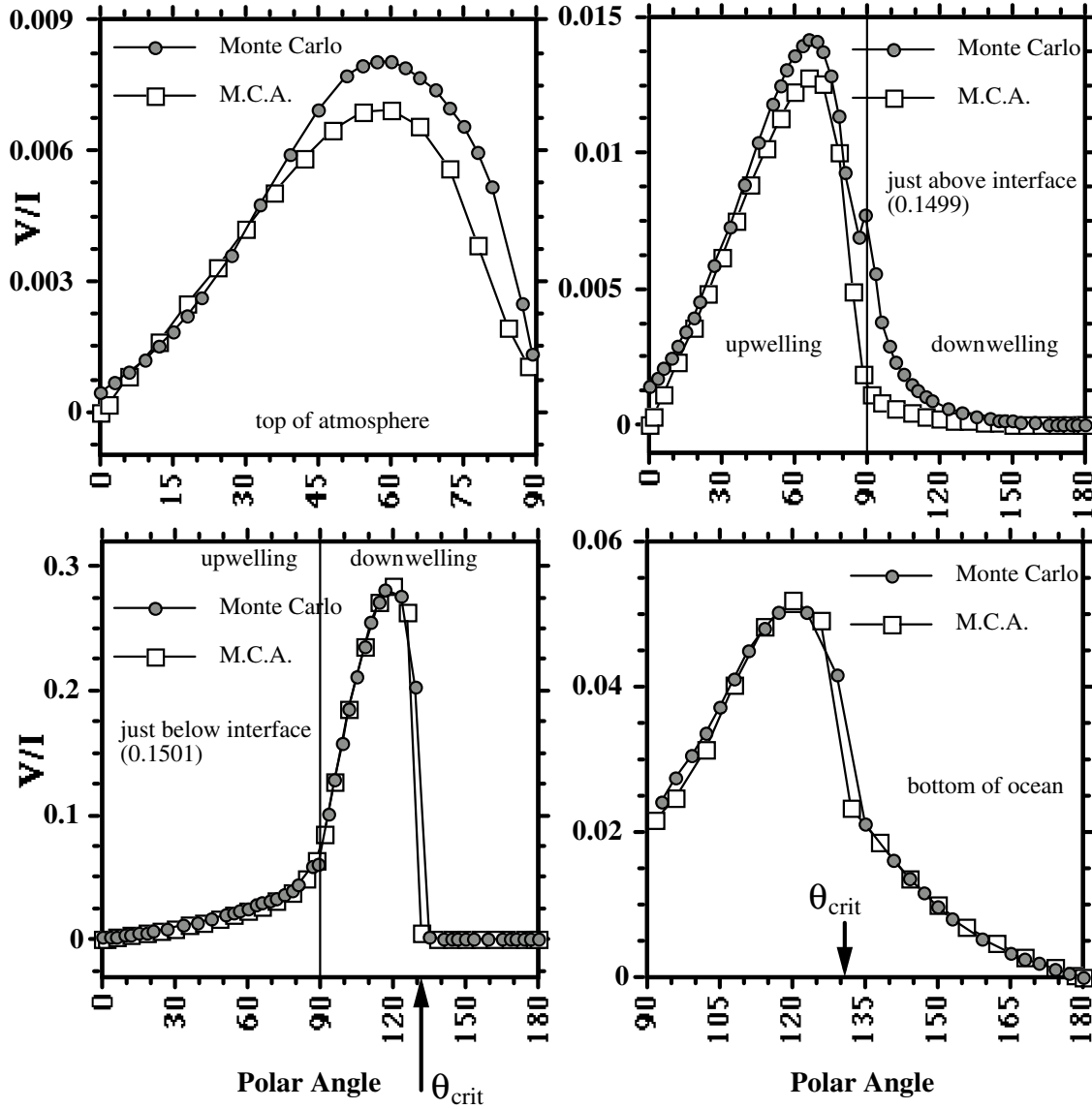
- a) Complete Mueller matrix calculations for a passive source (the sun) illuminating a plane parallel inhomogeneous atmosphere-ocean system with a wind ruffled dielectric interface. This program uses a new statistical estimation technique that allows for the multiple scattering Mueller matrix to be computed at precise angles without any solid angle averaging. This work is being done by Hatcher Tynes, a Ph.D. candidate.
- b) We are investigating electromagnetic wave scattering from rough surfaces through computer simulation, with the goal of producing the Mueller matrix for a rough surface. A surface is modeled as a stochastic process with a mean square height distribution and a surface height correlation function, with heights and correlation lengths on the order of the wavelength of the field. A plane wave is incident on the surface, and the scattered field is calculated using the Kirchhoff tangent plane approximation for the boundary conditions and integrating over the entire surface. Shadowing effects from the geometry of the particular surface is accounted for to first order. The scattered fields for several realizations of surfaces with the same statistics are averaged, and from these the Mueller matrix is constructed. This work is being carried out by Deric Gray, a Ph.D. candidate.
- c) We have also developed a new Monte Carlo program to calculate the multiple scattered Mueller matrix from a target imbedded in a turbid medium. This program uses state-of-the-art estimation techniques to improve the statistics over conventional "brute force" methods. It also utilizes any symmetry properties of the target. The single scattered Mueller matrix for the target is a sine qua non for these calculations. This work is being carried out by Dr. Milun Rakovic, a postdoctoral colleague.

## **WORK COMPLETED**

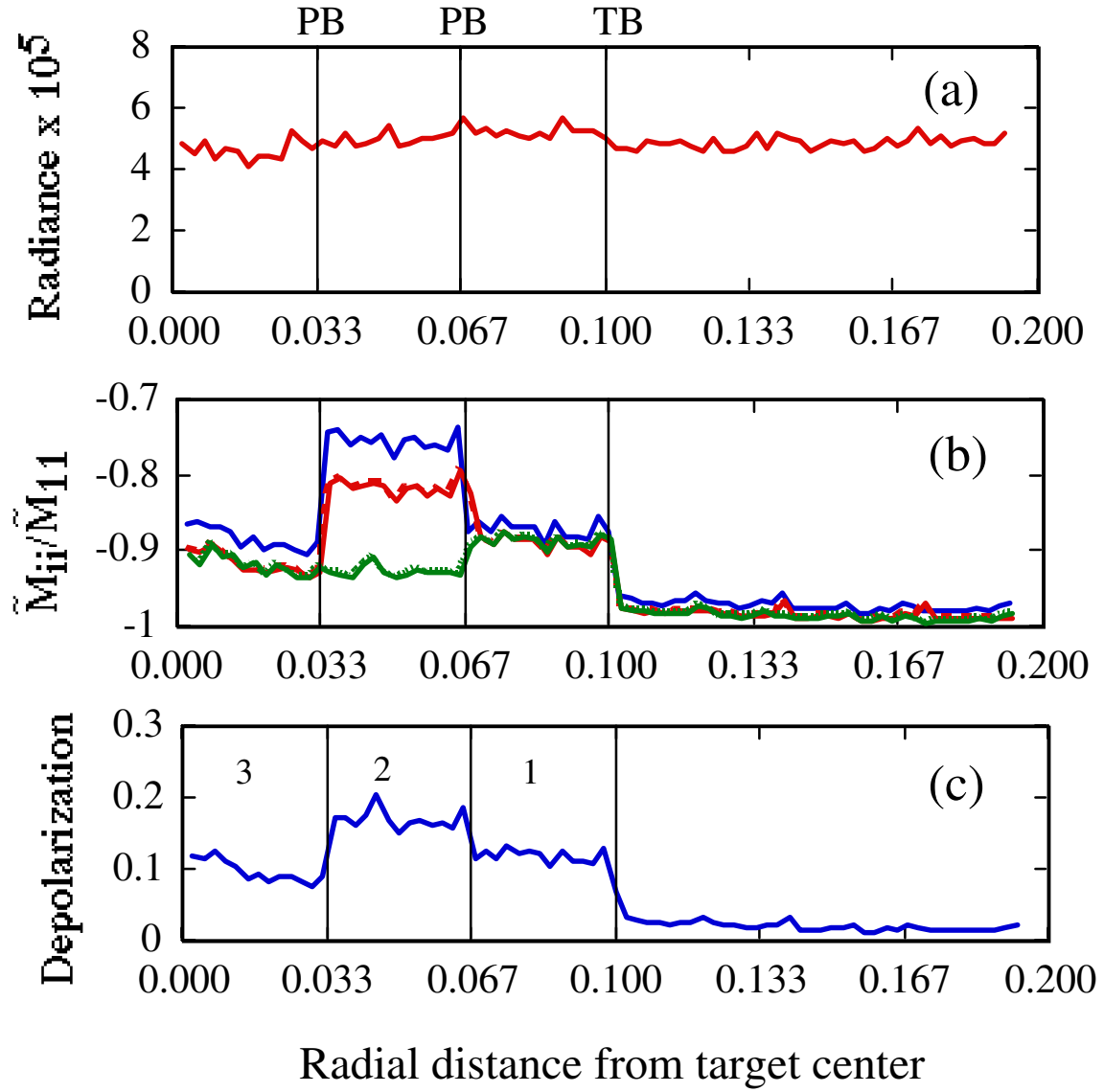
- a) Working with colleagues in biomedical engineering we have been able to measure and calculate the backscattered intensity patterns which arise when a turbid medium is illuminated with a polarized laser beam. The latest paper on this study has now appeared<sup>1</sup>.
- b) We have completed a study of the efficacy of using MMI to detect targets at optical depths where ordinary radiance imaging fails to resolve them. This interesting work has just appeared in Applied Optics<sup>2</sup>.
- c) Another phase of our collaborative work with Dr. Zege's group in Minsk has been completed which involved a comparison of her multi-component approach method with our Monte Carlo models for a coupled atmosphere-ocean system with an interface with no wind ruffling using a Henyey Greenstein volume scattering function. We have made the first comparisons of the strong ellipticity encountered underneath the interface of the ocean surface. The results of this study are being submitted to Applied Optics.

## RESULTS

We were able to show (see Fig. 1) for the first time that the strong degree of circular polarization (ratio of  $V/I$ ) which occurs just beneath the ocean interface (graph in lower left corner) can get as high as 30% but is greatly reduced by both multiple scattering in the atmosphere and in the ocean. The maximum at the top of the atmosphere is less than 1% whereas at the bottom of the ocean it is reduced to roughly 5%. These graphs also show the very nice agreement obtained for the ratio of  $v/I$  between the Monte Carlo approach and the multi-component approach of Zege. It should be noted that this quantity is by far the most difficult quantity to compute in radiative transfer theory.



**Fig. 1** Comparison between the Multi-component Approximation of Zege *et. al.* and the estimation Monte Carlo technique of Kattawar and Tynes. The model used here is a plane-parallel atmosphere-ocean system ( $\bullet \bullet_{atm} = 0.15$  and  $\bullet \bullet_{ocn} = 1.0$ ) with a smooth surface and conservative (single scatter albedo equal to one) Henyey-Greenstein scattering in both layers ( $g = 0.75$ ). The index of refraction of the ocean is 1.338. Here the degree of circular polarization is plotted versus the detector polar angle for four detector depths; at the top of the atmosphere, just above the interface, just below the interface and at the bottom of the ocean. The detectors at the interface show that the circular polarization of the light is due primarily to reflection from the interface. This is also seen at the top and bottom of the system since  $V/I$  is largest in the region where the dominant contribution is from reflected light.



**Fig. 2** Detected signal as a function of the radial distance from the target center. Target distance is 2 mfp and the sequence of the target regions is 3 - painted surface, 2 - polarization preserving, and 1-depolarizing.

Dashed vertical lines correspond to polarization boundaries (PB) inside the target, while solid vertical lines correspond to target - medium boundary (TB).

- a) Scalar radiance for the case of unpolarized incoming light beam of unit irradiance.
- b) Normalized diagonal matrix elements.
- c) Depolarization index.

In Fig. 2 we show how MMI can be used to detect targets that become non-detectable when using ordinary radiance imaging. We have imbedded a circular target at two mfp (mean free paths) in from a laser source in a highly scattering medium such as ocean water and show the returned signal as a function of radial distance away from the center of the target. The two vertical dashed lines mark the boundaries where different polarization properties were assigned to the target and the solid vertical line marks the boundary of the target. What is remarkable about this figure is that even though we have lost contrast with the background using ordinary radiance imaging (Fig. 2a), we can still see both the texture and boundary of the object using certain diagonal elements of the Mueller matrix which we call the depolarization index. For more of the details on this study see reference 2.

## **IMPACT/APPLICATION**

We now feel that from some of our preliminary work on Mueller matrix imaging, we will have new and more powerful tools for remotely sensing the atmosphere-ocean system. We also believe that it will lead to better and more comprehensive target detection in turbid media. What is desperately needed in all MMI work is the single scattered Mueller matrix for the types of targets one is trying to detect.

Our Monte Carlo programs for laser scattering from turbid media are presently being used to study light scattering from living tissue. The only thing that is slowing the process is the fact that the Mueller matrix for both normal and malignant tissue is not known.

Another very significant application of MMI is the detection of biological aerosols dispersed in the atmosphere.

## **TRANSITIONS**

Our Monte Carlo passive source Stokes vector programs are being used to check a different method for solving the equations of transfer with full Stokes vector treatment developed by Dr. Eleonora Zege and her group in Minsk, Belarus. Some of this work was supported by a CRDF grant.

## **RELATED PROJECTS**

Our inelastic scattering code is being used in a joint project with Dr. E. S. Fry to study the feasibility of using Brillouin scattering to measure the speed of sound as a function of depth in the ocean. This project is funded by the Texas Advanced Technology Program.

We are working closely with colleagues in the Bioengineering Department as well as the M.D. Anderson Cancer Center to determine the feasibility of using polarimetry to detect pre-cancerous skin lesions. This project has partial funding by the NIH.

We have also used our time-of-flight Monte Carlo code to check for pulse stretching from lidar returns above the ocean surface for Dr. Norris Keeler with Kaman Diversified Technologies Corp.

## **REFERENCES**

1. M. J. Rakovic, G. W. Kattawar, M. Mehrubeoglu, B. D. Cameron, L. V. Wang, S. Rastegar, and G. L. Cote, "Light backscattering polarization patterns from turbid media: theory and experiment," Appl. Opt. 38, 3399-3408, 1999
2. G. W. Kattawar and M. J. Rakovic " Virtues of Mueller Matrix imaging for underwater target detection" Appl. Opt. 38, 6431-6438, 1999

## **WEB ADDRESSES**

<http://physics.tamu.edu/~trouble>

<http://physics.tamu.edu/~rainman>